The mid-infrared transmission spectra of Antarctic ureilites

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Abstract—The mid-infrared ($4000-450$ cm^{-1}; $2.5-22.2$ μm) transmission spectra of seven Antarctic ureilites and 10 Antarctic H-5 ordinary chondrites are presented. The ureilite spectra show a number of absorption bands, the strongest of which is a wide, complex feature centered near 1000 cm^{-1} (10 μm) due to Si-O stretching vibrations in silicates. The profiles and positions of the substructure in this feature indicate that Mg-rich olivines and pyroxenes are the main silicates responsible. The relative abundances of these two minerals, as inferred from the spectra, show substantial variation from meteorite to meteorite, but generally indicate olivine is the most abundant (olivine:pyroxene = 60:40 to 95:5). Both the predominance of olivine and the variable olivine-to-pyroxene ratio are consistent with the known composition and heterogeneity of ureilites. The H-5 ordinary chondrites spanned a range of weathering classes and were used to provide a means of addressing the extent to which the ureilite spectra may have been altered by weathering processes. It was found that, while weathering of these meteorites produces some weak bands due to the formation of small amounts of carbonates and hydrates, the profile of the main silicate feature has been little affected by Antarctic exposure in the meteorites studied here. The mid-infrared ureilite spectra provide an additional means of testing potential asteroidal parent bodies for the ureilites. At present, the best candidates include the subset of S-type asteroids having low albedos and weak absorption features in the near infrared.

INTRODUCTION

Infrared spectroscopy provides a powerful technique for probing the molecular structure of materials since the positions, strengths, and profiles of the absorption features provide information about the chemical functional groups present and, to a lesser extent, about the longer range crystalline order of the material. Silicate minerals are particularly well suited for study by infrared spectroscopy because they can be well characterized in the laboratory by other techniques and because their different crystalline structures produce characteristic absorption bands. (For an excellent compilation of discussions on the infrared spectroscopy of minerals, see Farmer, 1974.)

A particularly useful application of this technique involves the comparison of the spectra of mineral standards and meteorites with telescopic observations of celestial objects. These studies allow one to identify (or rule out) potential candidate parent bodies for the different types of collected meteorites, and to infer mineralogical information from the telescopic data. Extensive comparisons have been made between meteorites and asteroid data in the near infrared ($16,600-4000$ cm^{-1}, $0.6-2.5$ μm) (*cf.* Gaffey, 1976; Gaffey and McCord, 1979; Chapman and Gaffey, 1979). Comparisons of meteorites and cosmic dust have also been made in the middle infrared ($4000-400$ cm^{-1}, $2.5-25$ μm) to asteroids (*cf*,. Feierberg *et al.*, 1983) and comets (*cf.*, Sandford and Walker, 1985; Bregman *et al.* 1987; Campins and Ryan, 1989; Hanner *et al.* 1990).

The past emphasis on comparisons in the near infrared is largely due to the greater ease with which telescopic data in this spectral region can be obtained. Also, the spectra of asteroids and comets in this region are dominated by reflected sunlight, while their mid-infrared spectra are dominated by thermal emission. As a result, the near infrared spectra are often easier to interpret. There are some advantages to spectroscopy in the mid-infrared, however. Absorption features in this region are primarily due to interatomic vibrations and therefore contain information about the composition and symmetry of the chemical functional groups present, and to a lesser extent, the longer range order of the functional groups. As a result, middle infrared spectra can provide additional mineralogical information not available from near-infrared spectra.

Mid-infrared laboratory spectra of many different meteorite classes are already available for comparison with telescopic data. One of the largest compilations in the literature is that of Sandford (1984). This paper presented and discussed the $4000-400$ cm^{-1} ($2.5-25$ μm) transmission spectra of members from the following meteorite groups: LL, L, and H ordinary chondrites, CO, CV, CI, and CR carbonaceous chondrites, enstatite chondrites, aubrites, eucrites, howardites, diogenites, mesosiderites, nakhlites, and shergotites. Examples of additional mid-infrared transmission studies involving smaller numbers of meteorites can be found in Knacke and Krätschmer (1980), Miyamoto (1987a, b), and Wagner *et al.* (1988). A compilation of $4000-750$ cm^{-1} ($2.5-13.5$ μm) reflectance spectra of a wide variety of meteorites can be found in Salisbury *et al.* (1991). (The latter paper also includes an excellent discussion of the spectral effects of the reflection process.)

Ureilites represent one of the few classes of meteorites that have not been studied in any detail in the infrared, either in transmission or reflectance. Near-infrared spectra of several ureilites can be found in Gaffey (1976) and mid-infrared reflectance spectra of two ureilites (Dingo Pup Donga and PCA 82506) can be found in Salisbury *et al.* (1991). Further infrared spectral characterization of the ureilite meteorite class is desirable because these meteorites represent a unique class of objects whose origin is the subject of some controversy, and ureilite spectra can be used to help constrain the potential asteroid source(s) for this meteorite class. Potential parent bodies for the ureilites include the abundant class of S-type asteroids, especially those having low albedos and weak features in the near infrared (Gaffey *et al.*, 1989, 1993).

Ureilites are shocked achondritic breccias composed primarily of millimeter-sized olivine-pigeonite aggregates whose structure and composition suggest formation at high temperatures, and a carbonaceous matrix that evidently reacted with the silicates to produce Mg-rich silicates plus metallic iron (see Dodd, 1981 and Goodrich, 1992 for good general reviews). The aggregates are dominated by Mg-rich olivine ranging from Fo$_{76}$ to Fo$_{97}$, with most falling between Fo$_{76}$ and Fo$_{85}$ (Takeda, 1991). The aggregates contain subordinate clinopyroxene. The olivine abundance is typically about twice that of the pyroxene, although there are a few reported examples where their abundances are approximately equal. The composition of the

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pyroxenes varies widely between meteorites, especially in Ca content. The dark matrix in which the aggregates are embedded is composed principally of graphite, diamond, lonsdaleite, Ni-poor metal, and troilite (Vdovykin, 1970; Berkley *et al.*, 1976, 1978, 1980). The texture and mineralogy of these phases suggests that these meteorites have been subjected to variable, but typically intense, shock metamorphism (Lipschutz, 1964; Vinogradov *et al.*, 1968).

Several subclassification schemes exist for ureilites (*cf.*, Vdovykin, 1970; Berkley *et al.*, 1978, 1980). Here I will make use of the subclassifications of Berkley *et al.* (1978, 1980) in which the ureilites are divided into three groups based largely on the Mg/Fe ratio of the olivines. Type 1, represented by meteorites like Goalpara and North Haig, consists of fine-grained olivines having a mean composition of about Fo_{85}, larger graphite-diamond intergrowths, and abundant pyroxene. Type 3, represented by meteorites like Novo Urei and Dingo Pup Donga, consists of more coarse-grained olivines having a mean composition of about Fo_{79}, small graphite-diamond intergrowths, and less pyroxene. One meteorite, Havero, lies intermediate to these two classes and is assigned to Type 2.

While there is no lack of data on these meteorites, the history and genesis of the ureilites remains enigmatic, largely because it is clear this history is complex (Berkley and Jones, 1982; Goodrich *et al.*, 1987; Goodrich, 1992). The evolutionary history of the ureilites included several important events, including (1) the formation of the silicate assemblage by fractional crystallization of a magma or as a residue of partial melting, (2) mixing with C-rich material, and (3) simultaneous or subsequent processing by impact shock. At present, at least five different models for the formation of ureilites have been suggested. These include suggestions that ureilites are (1) partial melt residues that were injected with C (Boynton *et al.*, 1976; Wasson *et al.*, 1976), (2) intrusive igneous cumulates formed from C-rich magmas (Berkley *et al.*, 1976, 1980; Berkley and Jones, 1982; Berkley, 1986; Goodrich *et al.*, 1987), (3) nebular condensates that underwent high-temperature recrystallization during planetesimal collisions (Takeda *et al.*, 1980, 1988; Takeda, 1987), (4) paracumulates derived from collisionally disrupted partially molten asteroids (Warren and Kallemeyn, 1988), and (5) impact melt products of CV-chondrite-like material (Rubin, 1988).

In an attempt to better quantify the mid-infrared spectral properties of ureilites, I have carried out a study of the $4000-450$ cm^{-1} ($2.5-22.2$ μm) spectra of seven Antarctic ureilites; ALHA 77257, ALHA 81101, EET 87511, EET 87517, LEW 85328, META 78008, and PCA 82506. This group of meteorites contains members of both the Type 1 and Type 3 subclasses and spans the range of Antarctic weathering classes. It is well known that Antarctic meteorites have been effected to varying degrees by weathering (*cf.*, Gooding, 1981) and this weathering can affect the spectral characteristics of the meteorites (Miyamoto, 1989, 1991). Thus, the determination of the spectral characteristics of ureilites requires an understanding of the spectral effects of weathering. To help with this understanding, a number of Antarctic H-5 ordinary chondrites that span a range of weathering classes were also examined. The ordinary chondrites studied were LEW 85338, LEW 85341, LEW 85393, LEW 86501, LEW 86534, LEW 87095, LEW 87205, LEW 87267, and LEW 87268.

In the following section, I discuss the experimental techniques used to obtain the spectra of the meteorite samples.

The results of these studies and a discussion of the implications of these results is also presented.

SAMPLES AND LABORATORY PROCEDURES

All the samples examined in this study were kindly provided by the Meteorite Working Group. A summary of the samples is given in Table 1. The experimental techniques used were identical to those described in Sandford (1984). Since the earlier paper gives an extensive discussion of the techniques and sample selection criteria used, only a brief summary will be given here.

The spectra were taken using a Nicolet 740 Fourier transform infrared spectrometer equipped with a globar source, a KBr beamsplitter, and a Hg-Cd-Te detector. Spectral coverage extended from 7000 to 450 cm^{-1} (1.4 to 22 μm) and spectra were taken at resolutions of both 4 and 1 cm^{-1}. It was found that there was no appreciable difference between spectra of the same samples taken at the two different resolutions. This is not surprising since the absorptions caused by silicates are broadened by solid state effects.

Meteorite samples were mounted using a standard KBr pellet technique. Every attempt was made to pick a relatively uniform aliquot from each of the provided meteorite samples. Fusion crust was avoided, both when the sample was selected at JSC, and then again when the infrared aliquots were prepared. Typically, one to three mg of sample were added to 200x the sample weight of KBr. The mixture was then ground mechanically in an all-steel ball mill for 1 min, and pellets were formed by compressing 100 mg of the resulting powder in a 1.5-cm diameter die at 1.1×10^8 Pa for 1 min. The resulting variability in sample density and column depth between the various meteorite samples is expected to be less than 5%.

The olivine-pigeonite aggregates in ureilites are typically 0.1–2.0 mm in diameter with an average of about 1 mm (*cf.*, Berkley, 1986), but domains as large of 7 mm have been reported. Thus, there exists the possibility that some of the small samples described above could be dominated by local heterogeneities and thus fail to be representative of the meteorite as a whole. In order to minimize this possibility, all the meteorite samples were gently ground and mixed manually before the one to three mg aliquot was selected for further grinding and mixing with KBr. The amount of material available for hand grinding varied from meteorite to meteorite, but all samples contained between 50 and 100

TABLE 1. Summary of the meteorites examined in this study.

Sample Number	Classification[†]	W[‡]	F[‡]	%Fa[‡]	%Fs[‡]	Ratio[*]
ALHA 77257,101	Ureilite (Type 1)	Ae	B	13	12	80:20
ALHA 81101,30	Ureilite (Type 3)	A/B	B	10–22	–	70:30
EET 87511,19	Ureilite (Type 1)	B	A	14	12	95:5
EET 87517,16	Ureilite (Type 1)	B/C	A	8	8	45:55
LEW 85328,31	Ureilite (Type 3)	B/C	A	20	17	85:15
META 78008,39	Ureilite (Type 3)	B	B	22	13	65:35
PCA 82506,73	Ureilite (Type 3)	A/Be	A	21	18	75:25
LEW 85338,4	H-5 chondrite	B	B/C	16	14	55:45
LEW 85341,5	H-5 chondrite	C	A	17	15	50:50
LEW 85393,4	H-5 chondrite	Be	B	18	15	60:40
LEW 85405,5	H-5 chondrite	B/C	A/B	19	16	55:45
LEW 86501,3	H-5 chondrite	C	B	18	16	55:45
LEW 86534,11	H-5 chondrite	B/C	A/B	18	16	55:45
LEW 87095,4	H-5 chondrite	A/B	A	17	15	55:45
LEW 87205,3	H-5 chondrite	B/Ce	B	17	15	50:50
LEW 87267,5	H-5 chondrite	Ce	B	18	16	45:55
LEW 87268,4	H-5 chondrite	B/Ce	A	18	16	55:45

† The ureilite type listed is based on the two major groups defined by the olivine mg criteria of Berkley *et al.* (1978, 1980). Type 1 is centered at $Fo_{84.4}$ and Type 3 is centered at $Fo_{78.9}$.
‡ W = Weathering; F = Fracture. Data From Score and Lindstrom (1990).
* Olivine to pyroxene. As derived from the infrared spectra presented in Fig. 3.

mg. In addition, whenever a spectrum was obtained that reflected the presence of only one mineral type, a second pellet was made and measured to confirm the first spectrum.

RESULTS

The $4000-450$ cm^{-1} spectra of the seven ureilites are shown in Fig. 1. They are arranged in order of increasing weathering class with the most weathered meteorites at the bottom. The spectra of the comparison H-5 ordinary chondrites are shown in Fig. 2 and are ordered by weathering class in the same manner as the ureilites. All the observed absorption bands are superimposed on a baseline that decreases in transmission to higher frequency due to wavelength-dependent scattering. This effect is more a function of sample grain size than of sample composition. The scattering baseline has been removed in Fig. 3, which shows the ureilite spectra between 1500 and 600 cm^{-1} ($6.7-16.7$ μm), the region spanning the strong absorptions associated with Si-O stretching vibrations. The baseline removal was done using algorithms provided with the spectrometer software to make the maximum in the continua in the
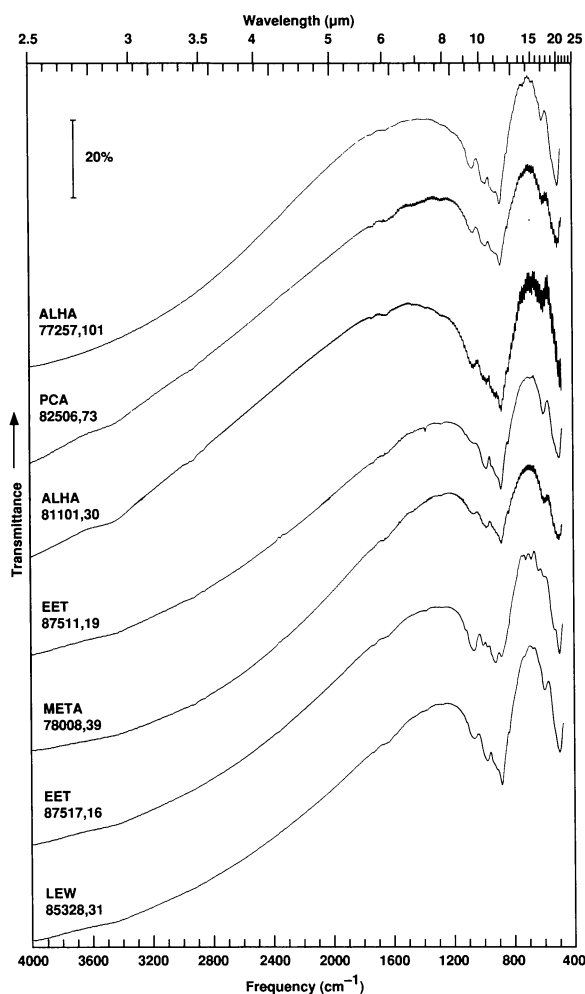
$2000-1500$ cm^{-1} and $750-650$ cm^{-1} ranges straddling the Si-O silicate feature correspond to 100% transmission. The ureilite spectra in Fig. 3 are grouped according to their Type 1 and 3 subclassifications. The spectra of olivine and pyroxene standards have been added to the bottom of the figure for comparison.

DISCUSSION

Contaminants and Weathering Products

The spectra of all the meteorites (ureilites and ordinary chondrites) are dominated by two wide, complex absorption
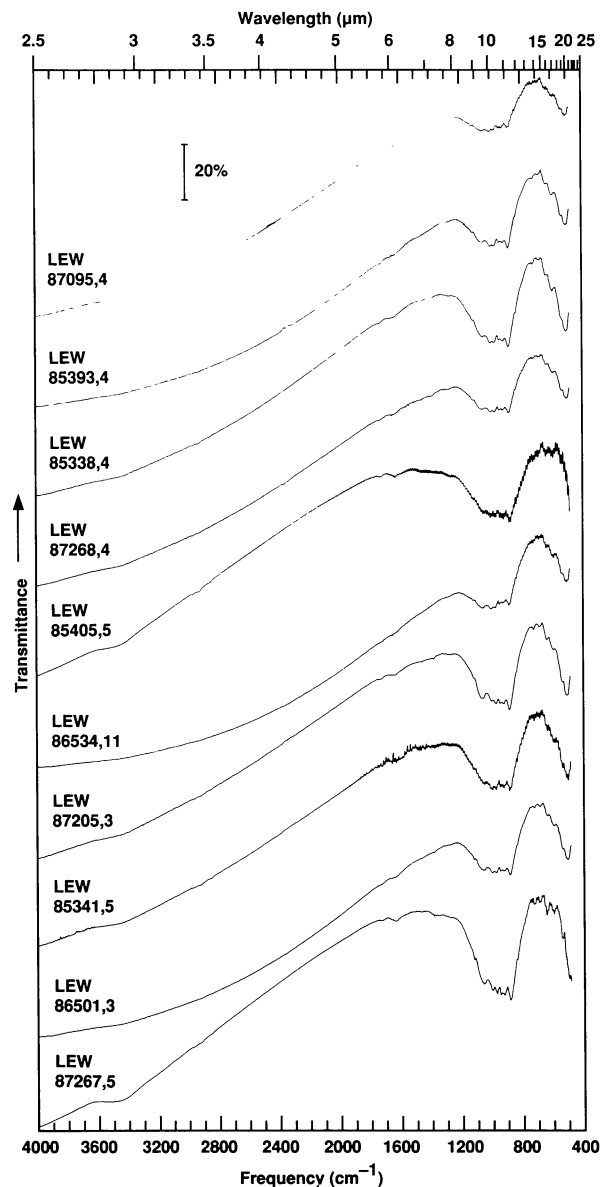

FIG. 1. The infrared transmission spectra from 4000 to 450 cm^{-1} ($2.5-22.2\mu$m) of seven Antarctic ureilites. The ureilites are ordered by weathering classification, with the least weathered samples at the top and the most weathered samples at the bottom. The spectra are offset from each other by an arbitrary amount for clarity. The scale bar corresponds to approximately 20% transmission.

FIG. 2. The infrared transmission spectra from 4000 to 450 cm^{-1} ($2.5-22.2\mu$m) of 10 Antarctic H-5 ordinary chondrites. The meteorites are ordered by weathering classification, with the least weathered samples at the top and the most weathered samples at the bottom. The spectra are offset from each other by an arbitrary amount for clarity. The scale bar corresponds to approximately 20% transmission.
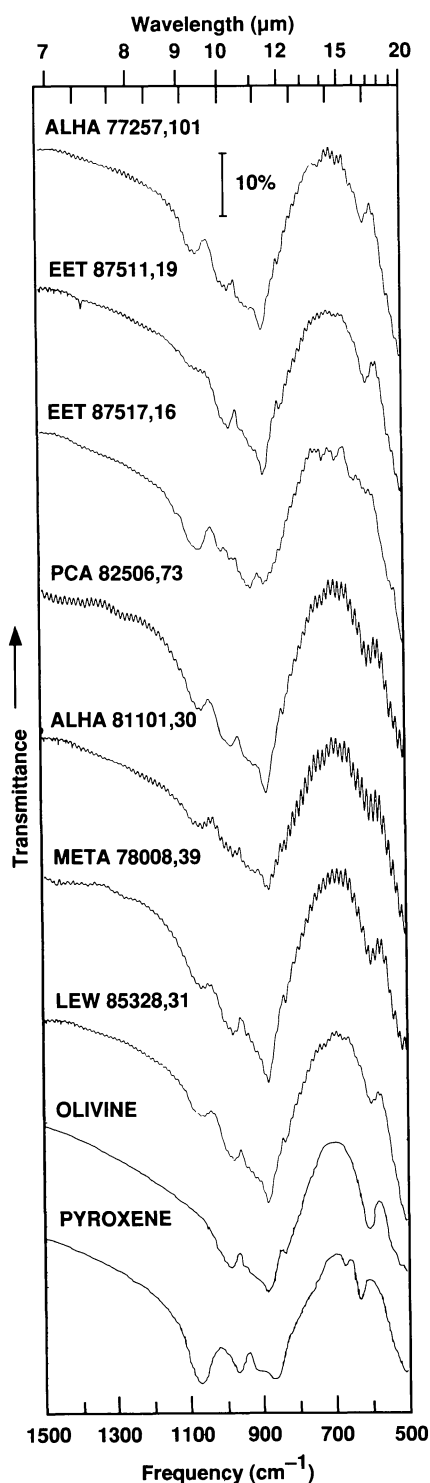
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Wavelength (μm)

ALHA 77257,101

10%

EET 87511,19

EET 87517,16

PCA 82506,73

ALHA 81101,30

META 78008,39

LEW 85328,31

OLIVINE

PYROXENE

Transmittance

1500 1300 1100 900 700 500

Frequency (cm^{-1})

FIG. 3. The infrared transmission spectra from 1500 to 600 cm^{-1} (6.7–16.7 μm) of the seven ureilites shown in Fig. 1 and terrestrial olivine (Mg$_{1.67}$Fe$_{0.33}$SiO$_4$) and pyroxene (Mg$_{1.67}$Fe$_{0.33}$Si$_2$O$_6$) standards. The prominent absorptions in these spectra are due to Si-O stretching vibrations (features near 1000 cm^{-1}) and O-Si-O bending vibrations (features near 500 cm^{-1}) of the silicates within the samples.

features centered near 1000 and 500 cm^{-1} (10 and 20 μm), but many of the spectra also show other, weaker features. The weaker features include a pair of absorption bands associated with hydration, a broad band centered near 3450 cm^{-1} (2.90 μm; O-H stretch) and a narrower feature that falls near 1640 cm^{-1} (6.10 μm; H-O-H bend). Most of the spectra also contain a weak trio of bands at about 2970, 2930, and 2850 cm^{-1} (3.37, 3.41, and 3.51 μm). The positions and relative strengths of these three bands are characteristic of aliphatic C-H stretching vibrations. Finally, several of the spectra contain a band or bands between 1460 and 1380 cm^{-1} (6.8–7.3 μm). Mineral bands in this region are characteristic of carbonates, and some sulfates.

Comparison of the original meteorite spectra with spectra taken from KBr pellet blanks, *i.e.*, sample pellets made in the exact manner described earlier but with no sample material added, demonstrated that most of the absorption in the 3450 and 1640 cm^{-1} hydration bands and essentially all of the absorption in the 2970, 2930, and 2850 cm^{-1} aliphatic C-H bands was due to contaminants absorbed into the KBr during preparation of the sample pellets. These absorption contributions were largely removed by re-ratioing the original single beam meteorite spectra by the appropriate single beam spectra of the KBr blanks. All the spectra in Figs. 1 and 2 were ratioed in this manner. When the contributions due to the KBr were removed it was found that some of the meteorite spectra still exhibited residual hydration bands and that none of the absorption bands between 1460 and 1380 cm^{-1} were removed. While it is possible that the materials responsible for these residual bands are original to the meteorites, it is more likely that these features are largely due to the presence of small amounts of weathering products (*cf.*, Gooding, 1981; Miyamoto, 1989, 1991). There is a general tendency for these bands to be stronger in the meteorites showing the greatest weathering, although there are exceptions. In any event, since these features may not be representative of the unaltered meteorites and since they are not expected to be diagnostic of the anhydrous minerals known to dominate these meteorite types, they will not be discussed further here.

The Meteoritic Silicate Features—The broad absorption features centered near 1000 and 500 cm^{-1} (10 and 20 μm) are due to Si-O stretching and O-Si-O bending vibrations, respectively. The detailed profiles of these bands depend on the crystalline structure of the silicates and can therefore be used to identify the major mineral components present (*cf.*, Farmer, 1974; Sandford, 1984). Comparison with the spectra of the terrestrial olivine and pyroxene standards (Fig. 3) indicates that the spectra of both the ureilites and the H-5 ordinary chondrites are dominated by these two minerals. In general, the ureilites show subfeatures near 1065, 980, 920, 885, 840, 600, and 500 cm^{-1} (9.4, 10.2, 10.9, 11.3, 11.9, 16.7, and 20.0 μm, respectively). Several of the samples, particularly EET 87511, EET 87517, and LEW 85328, also show weaker subfeatures near 1120, 1000, 950, 730, 690, 640, and 535 cm^{-1} (8.9, 10.0, 10.5,

The ureilites are grouped according to their Type 1 and 3 designations (Type 1: ALHA 77257, EET 87511, EET 87517; Type 2: PCA 82506, ALHA 81101, META 78008, LEW 85328). Within each group, the least weathered samples are at the top and the most weathered samples at the bottom. The spectra are offset from each other by an arbitrary amount for clarity. The scale bar corresponds to approximately 10% transmission.

13.7, 14.5, 15.6, and 18.7 μm, respectively). The profiles of the silicate features in the spectra of the H-5 ordinary chondrites are similar to those of the ureilites, differing only in that these samples produce all the bands listed above and that the relative strengths of the bands are different.

Comparisons of the positions, widths, and relative strengths of these features with the spectra of many olivine and pyroxene mineral standards having a variety of cation compositions (Sandford 1985) suggests the band assignments listed in Table 2. The band positions can all be associated with characteristic vibrational modes of olivines and pyroxenes, the sole exception being the band near 535 cm^{-1} (18.7 μm). This latter band is always weak and appears most frequently in the spectra of the H-5 chondrites, suggesting that it may be a weak, unidentified pyroxene band. Alternatively, this feature may be the result of Antarctic weathering (some clays and oxides produce a band at this position).

The overlapping of the various olivine and pyroxene features complicates the use of the spectra to derive the olivine-to-pyroxene ratios in the samples. However, several of the stronger subfeatures of olivine and pyroxene can be used as indicators of the presence of each of these minerals. In particular, an absorption feature near 1065 cm^{-1} is indicative of pyroxene and a feature near 885 cm^{-1} is characteristic of olivine. An approximate olivine-to-pyroxene ratio (accurate to ~10%) can be determined by comparing the ratio ($\%T_{885} - \%T_{1065}$)/$\%T_{1065}$ measured from the meteorite spectra with the same ratio measured from a series of spectra taken from standards having a range of predetermined relative abundances of these two minerals.

Using this technique the relative olivine:pyroxene abundances were found to cover a wide range extending from 45:55 to 95:5, with the olivine dominating in most of the samples (Table 1). For comparison, Takeda (1987) reports values for olivine:pigeonite of 48:52 for Y74659, 85:10 for Y790981, and 80:15 for ALHA 77257. Takeda *et al.* (1989) report additional olivine:pyroxene ratios for META 78008 and ALHA 82106. In ALHA 82106 they found total values of olivine:pyroxene = 65:26. In META 78008 they reported different values for different chips from the meteorite. Their Chip A had olivine:augite = 95:5, and Chip B had total olivine:pyroxene = 63:36.5. The general tendency for olivine to dominate is consistent with the observation that the modal pyroxene ratio (py = pyx/(pyx + oliv)) in ureilites usually ranges from <0.01 to 0.52 (Goodrich, 1992).

In the few cases where direct comparison with previous literature values is possible, the results of the spectral olivine-to-pyroxene abundance measurement agree quite well (to within 5% for ALHA 77257 and Chip B of META 78008). While it is not surprising that the infrared data confirm the general predominance of olivine in ureilites, the particularly close matches in olivine-to-pyroxene ratio may be somewhat fortuitous. The olivine-to-pyroxene ratio appears to vary substantially both from meteorite to meteorite and from location to location within a single meteorite (*e.g.*, Chips A and B of META 78008, Takeda *et al.*, 1989). Also, because of the relatively large grain sizes associated with ureilites (Berkley 1986), the small samples available for this spectral study will not necessarily be representative of the entire meteorites. An indication that meteoritic heterogeneity may be a factor in inferring the olivine-to-pyroxene ratio is provided by the observation that the average olivine-to-pyroxene ratio inferred from the infrared data for each of the Type 1 and Type 3 ureilite subgroups is essentially identical, while pyroxene is expected to be more abundant in the Type 3 meteorites (Berkley *et al.*, 1978, 1980).

However, the relative abundances of olivine-to-pyroxene derived from measurements of the H-5 ordinary chondrite spectra also match fairly well with expectations. The normative olivine-to-pyroxene ratio for H class ordinary chondrites is about 55:45 (see Table 4.1 of Dodd, 1981). This compares well with the range of 45:55 to 60:40 derived from the infrared data (Table 1). The presence of significant amounts of feldspars (~10% by volume) in the H ordinary chondrites, which will also produce absorptions in the 1000 cm^{-1} region, increases the spectral confusion and adds slightly to the uncertainty of the determination of the olivine-to-pyroxene ratio. Despite this additional complication, it is encouraging that the olivine-to-pyroxene ratios of the H-5 chondrites cluster more tightly than do the more heterogeneous ureilites. In any event, it is clear from the spectra of both the ureilites and the H-5 ordinary chondrites that properly sampled infrared data in the 1000 cm^{-1} region can be used to derive good approximations of sample olivine-to-pyroxene ratios.

Comparison with the Spectra of Other Meteorite Classes—The absorption spectra produced by the ureilites bear a strong resemblance to those seen in several other meteorite types. This is not surprising since the ureilite absorption positions and profiles are determined by the major minerals present and olivines and pyroxenes constitute the majority of the minerals in many types of meteorites. Comparison of the ureilite transmission spectra with those of LL, L, and H ordinary chondrites, CO, CV, CI, and CR carbonaceous chondrites, enstatite chondrites, aubrites, eucrites, howardites, diogenites, mesosiderites, nakhlites, and shergotites in the classes (see Sandford, 1984) reveal the closest matches with CO and CV carbonaceous chondrites. Again, this is not surprising since these two types of meteorites are rich in olivine. The ureilite

TABLE 2. Tentative mineral identifications to the various absorption bands in the spectra of ureilites and H-5 ordinary chondrites.

Band Position[†] (cm^{-1})	Band Position (μm)	Assignment[‡]
1120	8.9	Mg-rich pyroxene (w)
1065*	9.4*	Mg-rich pyroxene (s)
1000	10.0	Mg-rich pyroxene (s)
980	10.2	olivine (m)
950	10.5	Fe-rich (?) olivine (w)
920	10.9	pyroxene (s); Fe-rich olivine (m)
885*	11.3*	Mg-rich olivine (s)
840	11.9	pyroxene (s); Mg-rich olivine (w)
730	13.7	enstatite (w)
690	14.5	enstatite (w)
640	15.6	enstatite (w)
600	16.7	Mg-rich olivine (m,s)
535	18.7	???
500	20.0	olivine (s); pyroxene (m)

† Typical position observed in all the meteorites rounded to the nearest 5 cm^{-1}.

‡ Absorptions whose intrinsic relative strengths are weak, medium, and strong are designated as (w), (m), and (s), respectively.

* These two absorption features offer the best means of separating the relative contributions of olivine and pyroxene (see text).

spectra also bear some resemblance to the spectra of the more olivine-rich LL, L, and H ordinary chondrites. Thus, while the spectra of ureilites are diagnostic of the major minerals present, they do not allow for a completely unique identification of members of this meteorite class.

A search for the characteristic ureilite infrared features in the spectra of their potential asteroid source bodies could be very useful. At present, the best candidates fall in a subsection of the S class of asteroids having relatively low albedos and weak near-infrared absorption features (Gaffey *et al.* 1993). Interpretation of the mid-infrared spectra of asteroids will undoubtedly require comparisons to all the available laboratory data sets, both transmission spectra like those presented here, and reflectance spectra like those found in Salisbury *et al.* (1991). Also, since the flux from asteroids in this spectral region is usually dominated by thermal emission processes, some modelling will probably also be required. However, given that the spectral features in this region are so diagnostic of the minerals present, such an effort should be well worth while. Of course, the results presented here demonstrate that a match in the Si-O stretching region alone will not provide sufficient information for distinguishing different classes of meteorites containing abundant olivine, since other meteorite types could be responsible (for instance the CO and CV carbonaceous chondrites). As a result, spectral comparisons with asteroids in the mid-infrared will be most useful when used in conjunction with information derived from other spectral regions.

Comparison with the Spectra of Circumstellar and Interstellar Silicates—The infrared spectra of the meteorites can also be compared to the spectra of circumstellar and interstellar silicates. Comparison with the spectra of interstellar silicates is the simplest since these data are taken by observing a background star through intervening material, resulting in a spectrum containing bands in absorption. Thus, little or no modelling is required to comparisons to the meteorite data. Most absorption spectra of interstellar dust contain a relatively featureless Si-O absorption band (*cf.*, Merrill, 1979). This is generally interpreted as implying that interstellar silicates consist largely of amorphous materials rather than distinct, crystalline mineral phases. However, limited amounts of spectropolarimetry data indicate that the silicate feature in at least some of the spectra can be separated into several components, one of which is dominated by the characteristic 885 cm^{-1} (11.3 μm) band of crystalline olivines (Aitken *et al.*, 1988). Thus, the crystalline form of one of the dominant minerals in most meteorites and the most dominant mineral in ureilites exists as one of the components of interstellar dust.

It now appears that the same statement may be true of some circumstellar dust as well. A recent spectroscopy study of the dust disk around β Pictoris has revealed the presence of a silicate emission feature that contains spectral structure (Knacke *et al.*, 1993). The profile of the β Pic silicate emission feature is very similar to the spectrum of Comet Halley, which in turn can be well matched by the spectra from a mixture of the two interplanetary dust particle classes dominated by the minerals olivine and pyroxene (Sandford and Walker, 1985; Bregman *et al.* 1987). Thus, it appears that pyroxene and olivine may also be common in circumstellar dust as well. This is not too surprising since the material in the β Pic disk is probably very similar to the material that existed in our own solar system at that stage in its evolution.

CONCLUSIONS

The mid-infrared (4000–450 cm^{-1}; 2.5–22.2 μm) transmission spectra of seven Antarctic ureilites and 10 Antarctic H-5 ordinary chondrites have been presented. The spectra contain a number of absorption bands. The majority of the weaker absorptions are associated with trace contaminants and weathering products resulting from Antarctic exposure. The strongest absorptions produce complex features near 1000 cm^{-1} (10 μm) and 500 cm^{-1} (20 μm) that are associated with Si-O stretching and O-Si-O bending mode vibrations, respectively, of silicates.

The positions and profiles of the silicate features are diagnostic of the types and abundances of the minerals present. The silicate feature profiles in the spectra of both the ureilites and the H-5 ordinary chondrites indicate the samples are dominated by the minerals olivine and pyroxene with olivine being most abundant. The olivine-to-pyroxene ratios inferred from the infrared data (accurate to about 10%) fall in the range from 45:55 to 95:5 for the ureilites and between 45:55 to 60:40 for the H-5 chondrites, values consistent with the known mineralogy of these meteorite classes.

The mid-infrared spectra of the ureilites are very similar to those obtained from other meteorite classes that contain abundant olivines, especially the CO and CV carbonaceous chondrites. Thus, mid-infrared spectra, taken alone, do not constitute sufficient information to make a class identification, and potential asteroidal source bodies for the ureilites cannot be identified solely on the basis of their mid-infrared spectra. Spectral data from other frequency ranges will also be required.

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